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The return to the hard state of GX 339-4 as seen by Suzaku

P.-O. Petrucci¹, C. Cabanac², S. Corbel³, E. Koerding⁴, and R. Fender^{5,6}

¹ UJF-Grenoble 1 / CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274, Grenoble, F-38041, France

² Université de Toulouse, UPS-OMP, IRAP, Toulouse, France CNRS, IRAP, 9, av du Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France

³ Laboratoire AIM (CEA/IRFU - CNRS/INSU - Université Paris Diderot), CEA DSM/IRFU/SAP, F-91191 Gif-sur-Yvette, France

⁴ Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010;6500 GL Nijmegen;The Netherlands

⁵ University of Oxford, Department of Physics, Astrophysics, Denys Wilkinson Building, Keble Road, OX1 3RH, Oxford, UK

⁶ School of Physics and Astronomy, University of Southampton, Highfield, Southampton, SO17 1BJ, UK

Received .../Accepted ...

ABSTRACT

The reality of the disk recession is an information of prime importance to understand the physics of the state transitions in X-ray binaries. The microquasar GX 339-4 was observed by Suzaku five times, spaced by a few days, during its transition back to the hard state at the end of its 2010-2011 outburst. The 2-10 keV source flux decreases by a factor ~ 10 between the beginning and the end of the monitoring. Simultaneous radio and OIR observations highlighted the re-ignition of the radio emission just before the beginning of the campaign, the maximum radio emission being reached between the two first Suzaku pointings, while the IR peaked a few weeks latter. A fluorescent iron line is always significantly detected. Fits with a gaussian or Laor profiles give statistically equivalent results. In the case of a Laor profile, fits of the five data sets simultaneously agree with a disk inclination angle of ~ 20 degrees. The disk inner radius is $< 10 - 30 R_g$ in the first two observations but almost unconstrained in the last three due to the lower statistics. A soft X-ray excess is also present in these two first observations. Fits with a multicolor disk component give disk inner radii in qualitative agreement with those obtained with the iron line fits. The use of a physically more realistic model, including a blurred reflection component and a comptonization continuum, give some hints of the increase of the disk inner radius but the significances are always weak (and model dependent) preventing any clear conclusion concerning disk recession during this campaign. Interestingly, the addition of warm absorption significantly improves the fit of OBS1 while it is not needed in the other observations. The radio-jet re-ignition occurring between OBS1 and OBS2, these absorption features may indicate the natural evolution of the accretion outflows transiting from a disk wind, an ubiquitous characteristic of soft states, and a jet, signature of the hard states. The comparison with a long 2008 Suzaku observation of GX 339-4 in a persistent faint hard state (similar in flux to OBS5) where a narrow iron line clearly indicates a disk recession, is discussed.

1. Introduction

Multi-wavelength observation campaigns of microquasars, like those done in X-ray and Radio in the last 10 years, were crucial to bring to light the strikingly link between the ejection phenomena (mostly observed in radio) and the inner accretion flow, whose radiation seems to be the dominant component in the X-rays (e.g. Corbel et al. 2000, 2003; Coriat et al. 2011; Gallo et al. 2003). For instance, strong radio emission, interpreted by the presence of persistent jets (directly observed in a few cases, e.g. Dhawan et al. 2000; Stirling et al. 2001), is generally detected when the X-ray emission peaks at a few tens of keV, in the so-called hard state (e.g. Corbel et al. 2004; Fender et al. 2004). This X-ray emission is commonly believed to originate via inverse Compton process from a plasma of hot electrons (the so-called corona) scattering off UV/soft X-ray photons produced by the cooler part of the accretion flow. On the other hand, in the so-called soft state the radio emission is quenched (Fender et al., 1999; Corbel et al., 2000)

and the X-ray data are spectrally dominated by soft X-ray emission. This emission is generally interpreted as signature of a multi-color accretion disk component down to the last stable orbit R_{ISCO} .

In the past ten years, high energy resolution observations of several microquasars showed also the presence of highly ionized absorption features in their X-ray spectra. These features were interpreted as signature of ionized gaz in the close environment of the black hole, their blueshifts being indication of outflows or winds (e.g. Miller et al. 2004 hereafter M04, Miller et al. 2006c). It has been realized that these features were more specifically observed in the soft state (e.g. Ponti et al. 2012; Diaz Trigo et al. 2011; Diaz Trigo & Boirin 2012). These results suggest that, during outbursts, X-ray binaries may transit back and forth between disk-jet (in the hard state) and disk-wind (in the soft state) configurations (e.g. Neilsen & Lee 2009). However the exact interplay between ejection and accretion phenomena and the origin of the transition from one state to the others

Obs name	Obs ID	MJD	XIS03 Exp. ks	XIS 0-3 0.7-2 keV (s^{-1})	XIS 0-3 2-10 keV (s^{-1})	HXD/PIN 20-70 keV (s^{-1})	HXD/GSO 70-200 keV (s^{-1})
OBS1	405063010	55603.7	44.2	11.90 ± 0.02	10.22 ± 0.02	0.62 ± 0.01	0.96 ± 0.04
OBS2	405063020	55608.9	42.0	5.20 ± 0.01	6.55 ± 0.01	0.46 ± 0.01	1.05 ± 0.04
OBS3	405063030	55616.8	38.4	1.81 ± 0.01	2.80 ± 0.01	0.20 ± 0.01	0.74 ± 0.05
OBS4	405063040	55620.2	43.6	1.32 ± 0.01	2.09 ± 0.01	0.15 ± 0.01	0.74 ± 0.04
OBS5	405063050	55627.5	37.3	0.92 ± 0.01	1.50 ± 0.01	0.10 ± 0.01	0.56 ± 0.05

Table 1. Log of the 5 observations with their ID number, the corresponding date (in MJD), the sum of the XIS0 and XIS3 exposure time (each exposure being ~ 20 ks, the total exposure of the XIS0 and XIS3 instruments is about twice this time) and the count rates in the different Suzaku instruments. .

is still poorly known (see however the recent study done by Kalemci et al. 2013).

The commonly adopted toy-picture of the central regions of microquasars plays on the relative importance of the accretion disk and hot corona emission along the outburst (e.g. Esin et al. 1997; Done et al. 2007). The accretion disk is assumed to be present in between an outer and inner radius R_{out} and R_{in} while the hot corona is localized in between R_{in} and R_{ISCO} . In the hard state, $R_{in} \gg R_{ISCO}$ and the hot corona dominates the observed emission. The inner part of the accretion disk (close to R_{in}) is then cold, explaining its poor detection in the soft X-rays in this state. Reversely, in the soft states $R_{in} \sim R_{ISCO}$, i.e. the hot corona is no more present and the spectra are dominated by the accretion disk emission.

If this picture is correct, variations of the disk inner radius R_{in} should occur during the state transitions, first decreasing during the hard-to-soft transition but then increasing during the soft-to-hard one. This interpretation is apparently supported by the observations, in hard states, of weak reflection components (e.g. Gierlinski et al. 1997; Barret et al. 2000; Miller et al. 2002; Zycki et al. 1998; Joinet et al. 2007), the absence of relativistic broadening of the iron line in a few cases (e.g. Tomsick et al. 2009; Plant et al. 2013) and the absence of obvious thermal components (e.g. Poutanen et al. 1997; Dove et al. 1997; Remillard & McClintock 2006; Done et al. 2007; Dunn et al. 2010), all potential signatures of small and remote reflecting area.

The variable disk inner radius during state transitions then becomes a natural key ingredient in most theoretical models, controlling or resulting from the spectral and timing evolution of microquasars during the outburst (e.g. Esin et al. 1997; Meyer et al. 2000; Belloni et al. 2005; Remillard & McClintock 2006; Ferreira et al. 2006; Petrucci et al. 2008).

Recent XMM observations, much more sensitive, especially in the soft X-rays (i.e. below 2 keV), compared to the other existing X-ray missions, apparently ruled out the presence of a recessed disk in the hard states (e.g. Miller et al. 2006a,b). The long XMM observation monitored during the 2004 outburst of GX339-4 did not agree with a simple power-law although the system was in a typical, although bright ($\sim 10\% L_{Edd}$), hard state. According to the authors, a very strong soft excess as well as a broad emission feature around 6.4 keV were also present and well fitted by multicolor disk and a relativistically broadened emission line respectively. This suggests the presence of an accretion disk extending towards the vicinity of the black hole (but see below). SWIFT/XRT observations of

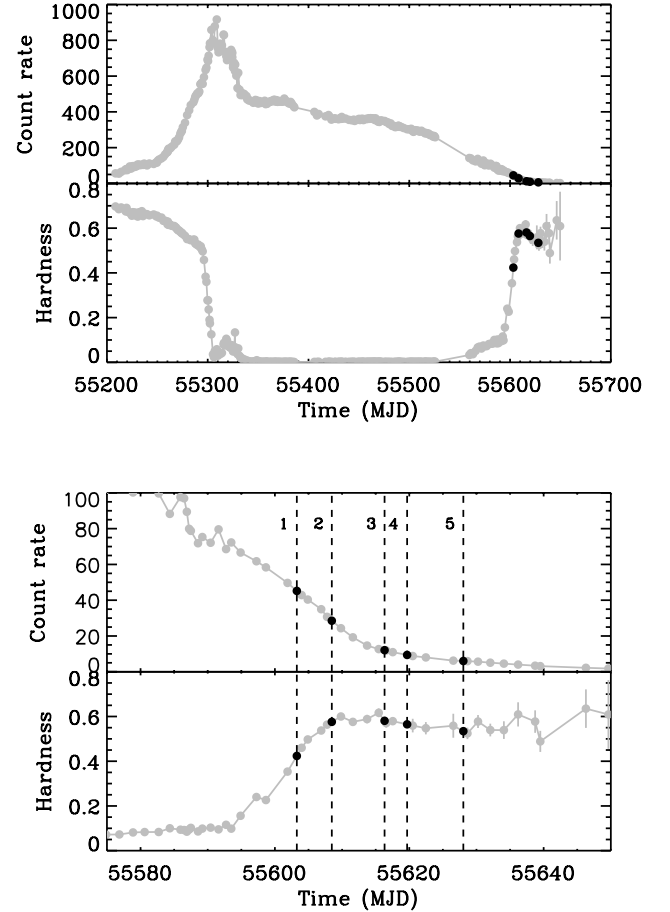


Fig. 1. **Top:** RXTE/PCA 3-20 keV count rate and hardness ratio light curves of the complete 2010-2011 outburst of GX 339-4. **Bottom:** A zoom of the end of the outburst, with the date of the 5 Suzaku observations indicated by the black dots and the vertical dotted lines.

XTE J1817- 330, during its decline to the hard state, led Rykoff et al. (2007) to the same conclusions i.e. no disk recession. From their SWIFT survey of stellar mass black holes, Reynolds & Miller (2013) do not find evidence for large-scale truncation of the accretion disk in the hard state either, at least for X-ray luminosities larger than $10^{-3} L_{Edd}$.

The estimates of inner disk radii based on continuum spectroscopy are subject however to considerable uncertainties (e.g. Merloni et al. 2000; Zimmerman et al. 2005;

Cabanac et al. 2009 hereafter C09) and different data analysis may give different conclusions. A recent re-analysis of the data used in Miller et al. (2006b) suggests that the observed broad iron line may be an artifact due to an improper correction of the pile-up in the MOS data (Done & Diaz Trigo, 2010). Suzaku pointing on the same source in its hard state has also shown that the spectrum could be consistent with a truncated disk (Tomsick et al., 2009). More specifically, by re-analyzing the whole SWIFT/XRT dataset of XTE J1817-330, C09 does observe a slight increase of the disk radius. This occurs apparently when the 2 -10 keV luminosity decreases below $\sim 5 \times 10^{-3} L_{Edd}$ ¹. These authors analyzed other sources in the same way and obtain similar, though less significant, results.

The reality of the disk recession is clearly an information of prime importance that we crucially need if we want to understand the physics of the state transitions. Confirming, and precisely measuring, this recession (if any) should allow to constrain and refine most of the present theoretical models. On the other hand, the absence of recession will imply to strongly reconsider our present understanding of the microquasar phenomenon.

We present in this paper a Suzaku campaign on the microquasar GX 339-4 aiming at catching the recession, if any, of the accretion disk during a soft-to-hard state transition. Sect. 2 detailed the observation and data treatment and Sect. 3 the data analysis. While the constraints on the disk inner radius, discussed in Sect. 4, prevent any clear conclusions concerning its recession, the observation of ionized absorbing features in the soft X-rays may suggest a disk wind whose properties may evolve during the transitions. These results are discussed in Sect. 5 before concluding.

2. Observations and data treatment

2.1. Suzaku Observations

GX 339-4 was observed five times (~ 20 ks each) by Suzaku at the end of its last outburst in February 2011, as soon as the source became visible by the satellite. The 5 observations were separated by a few days in order to follow the spectral evolution of the object all along its transition back to the hard state. The log of these observations is detailed in Tab. 1, with the corresponding dates. The RXTE/PCA 3-20 keV light curve of the complete 2010-2011 outburst of GX 339-4 is plotted at the top of Fig. 1 together with the hardness ratio². A zoom of the last part of the outburst, with the dates of the 5 Suzaku observations indicated by the vertical dotted lines, is shown at the bottom of Fig. 1.

For the data treatment we use the most up-to-date calibration files and the HEASoft version 11.6.1. We run the Suzaku XIS/HXD *aepipeline* (V1.1.0) tools to reprocess the data from scratch. We take care to pile-up effect in the XIS instrument by running first the *aeattcor2* tool which corrects Suzaku attitude data for the effects of "thermal wobbling" caused by thermal distortions of the satellite bodies³. Then we run the pile-up fraction estimation tool

pileest also released in the HEASoft package to estimate the amount of pileup in the XIS images and disregarded regions with $>10\%$ pileup fraction during the spectral extraction. Only the first two observations suffered from pileup (~ 19 and 10% for OBS1 and OBS2 respectively for the most central pixels) and a circular region of $\sim 10''$ radius in the central part of the image was excluded. We added together the XIS0 and XIS3 spectra. Unless specified in the text, the XIS spectra were all rebinned so that the minimum number of bins per resolution element is 5 in order to ensure a minimum number of counts per channel of 30^4 .

To create the background files in the XIS energy range we use the ftool *xisnxbgen* which estimates the non X-ray background spectrum of the XIS instrument. While the Cosmic X-ray Background is expected to be low in the XIS energy band, we take it into account following the recipe indicated in the ABC guide V4.0 (p. 81-82)⁵ but renormalized to the XIS FOV corresponding to the 1/4 window mode. The total X-ray background files (including the non-X-ray as well as the cosmic X-ray background) of the HXD/PIN instruments were computed using the ftools *hxdpinxbpi*⁶. For the non X-ray background, we use the "tuned" background files distributed by the HXD team and corresponding to our observations. These "tuned" background suffers from systematic uncertainties of about

⁴ For the rebin procedure, we use the tool PHARBN developed by M. Guainazzi and adapted to the XIS instrument

⁵ <http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/>

⁶ We do not include the GSO data in the spectral analysis due to their very poor statistics.

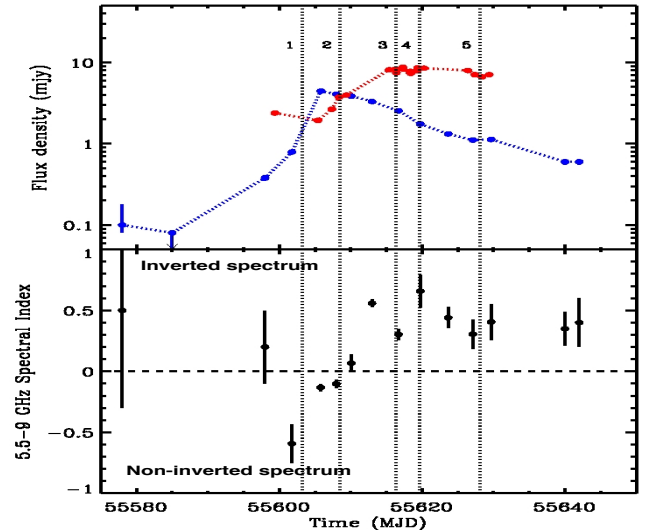


Fig. 2. Top: 5.5 GHz (blue) and H band (red) light curves. Bottom: Light curve of the 5.5-9 GHz spectral index. A positive spectral index corresponds to an inverted spectrum generally characteristic of optically thick synchrotron emission from a stratified jet (e.g. Blandford & Königl 1979). The dates of the 5 Suzaku observations are indicated by the vertical dotted lines (data from Corbel et al. 2013).

¹ Assuming a 10 solar masses black hole.

² The hardness ratio is defined as the ratio of the (5.7-9.5 keV) count rate over the (2.9-5.7 keV) count rate

³ <http://heasarc.gsfc.nasa.gov/ftools/caldb/help/aeattcor2.html>

1.3%⁷ that have been added to the PIN data during our fitting procedure.

Following the *ABC guide V.4.0 (chapter 5.7.2)*, the normalization of the HXD/PIN with respect to XIS is fixed to 1.16. The energy ranges for the XIS and HXD/PIN instruments are restricted to 0.7-10 keV and 20-70 keV respectively. In the following, we name the five observations OBS1, OBS2, OBS3, OBS4 and OBS5 (see Tab. 1).

2.2. Radio and IR observations

Simultaneous or quasi simultaneous radio observations were taken with the Australia Telescope Compact Array (ATCA) at 5.5 and 9 GHz (Corbel et al. 2013, hereafter C13). Simultaneous or quasi simultaneous optical and IR observations were taken with the SMARTS telescope (Buxton et al., 2012; Dinger et al., 2012). The corresponding light curves are reported at the top of Fig. 2 and the radio spectral index (between the 5.5 and 9 GHz band) is plotted at the bottom of the figure.

3. Results

3.1. Light curves

GX 339-4 was at the end of its outburst and, as expected, its X-ray flux decreases from OBS1 to OBS5. The count rates in the 0.7-2, 2-10, 20-70 and 70-200 keV ranges are indicated in Tab. 1 and indeed they all decrease during the campaign. Interestingly the decrease is much more pronounced in the softer energy range than in the harder ones. The 0.7-2 keV range count rate decreases by more than a factor 10 while it decreases by less than a factor 2 in the 70-200 keV range. This clearly indicates a spectral change of the X-ray emission.

As shown in Fig. 2, the radio emission begins to increase between MJD 55590-55600 and reaches a maximum between our two first Suzaku observations (\sim MJD 55605). The radio emission being generally associated with the presence of a jet, the increase of radio flux is interpreted as the reappearance of the jet while GX 339-4 is turning back to its hard state (see e.g. C13, Kalemci et al. 2013). This is well supported by the simultaneous increase of the radio spectral index (bottom plot on Fig. 2), which becomes positive after OBS2. Such inverted spectrum is characteristic of optically thick synchrotron emission from a stratified jet (e.g. Blandford & Königl 1979).

It is interesting to note that the RXTE/PCA hardness ratio (cf. Fig. 1) begins to increase a few days before the radio peak, the two events being clearly separated in time (see also Kalemci et al. 2013 for other outbursts). Concerning the H band emission, it reaches a local maximum about 10 days after the radio peak, in between OBS3 and OBS4 (see the discussion in C13).

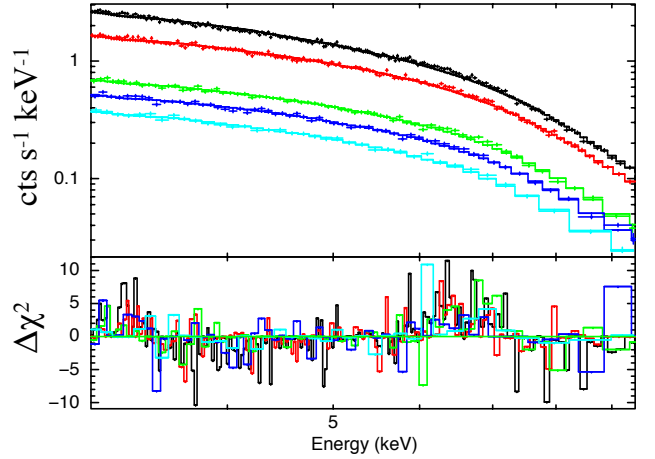


Fig. 3. Top panel: Folded spectra of the 5 Suzaku observations (OBS1 to OBS5 from top to bottom) fitted by a power law in the 3-10 keV energy range. **For clarity, only the XIS0+XIS3 spectra are plotted. They have been rebinned in order to have 30σ per bin.** The bottom panel shows the contributions to the χ^2 .

3.2. Spectral analysis

3.2.1. Above 3 keV: XIS data alone

We begin our spectral analysis on the Suzaku data above 3 keV, a spectral domain known to be dominated by the primary continuum. We first fit the XIS data only between 3 and 10 keV with a simple power law model. The best fit values for the photon index are reported in Tab. 2 and the folded spectra are plotted in Fig. 3. The photon index decreases rapidly between OBS1 and OBS2, from $\Gamma = 1.72 \pm 0.01$ to $\Gamma = 1.56 \pm 0.01$ and then stays roughly constant around 1.55 between OBS2 and OBS5.

Excesses close to 6-7 keV are visible especially in OBS1, 2 and 3, suggesting the presence of an iron $K\alpha$ line. We add a gaussian component and fit the spectra again. The fit improves very significantly for OBS1 ($\Delta\chi^2=143$), less for OBS2 and 3 ($\Delta\chi^2=29$ and 30 respectively) and even less for OBS4 and 5 ($\Delta\chi^2=14$) but the improvement is always significant (at more than 99% following the F-test⁸). The best fit parameter values are reported in Tab. 2. The contour plots of the line flux vs. line energy and line width vs. line energy for the 5 observations are plotted in Fig. 4.

The line flux is clearly decreasing between OBS1 and OBS2 (at more than 3σ). Then, between OBS2 and OBS5, it is consistent with a constant at a confidence level of $\sim 70\%$. Concerning the line energy, its highest value is reached in OBS3 with $E_{gauss} = 6.77 \pm 0.13$. The others measurement are consistent with a neutral iron line peaking at 6.4 keV. The significance of the variability of the line energy during the campaign is however less than 40%. The line width is consistent with a constant at a confidence level of $\sim 60\%$. It has an average value of $\sim 440 \pm 70$ eV potentially indicating some broadening.

⁷ see <http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/watchout.html>, item 16.

⁸ See however Protassov et al. (2002) about the usage of the F-test in line-like features.

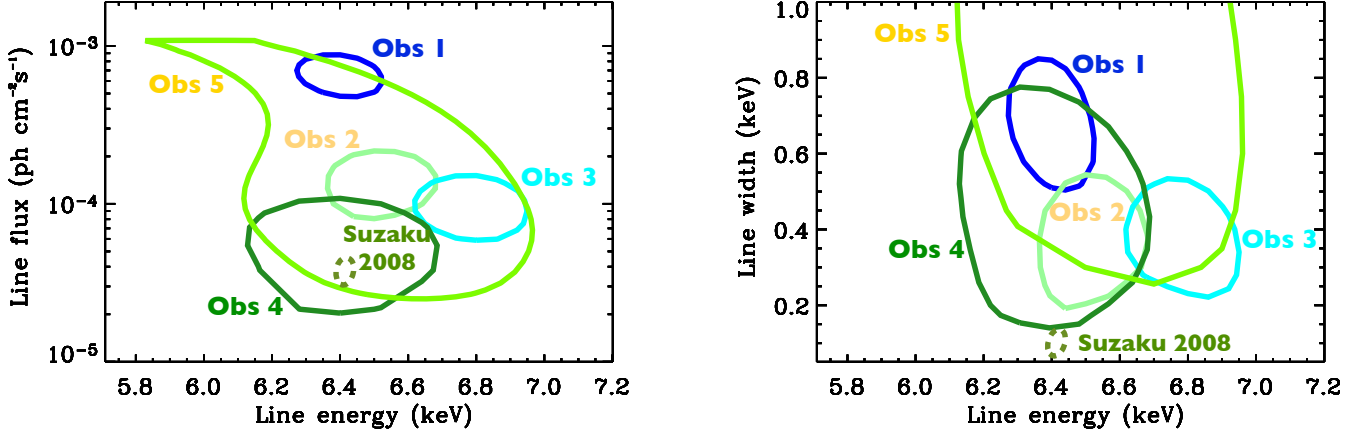


Fig. 4. The 90% contour plots line flux vs. line energy (**Left**) and line width vs. line energy (**Right**) from the best fits of the five XIS spectra with a POWER LAW + GAUSSIAN model in the 3-10 keV energy range. The dashed contour corresponds to the Suzaku observation of 2008 (Tomsick et al., 2009).

To test if the line broadening could be due to relativistic effects, we replace the gaussian profile by a Laor profile which is expected if the line emission is produced by an accretion disk around a black hole. To limit the number of free parameters, we fix the outer radius of the disk R_{out} to $400 R_g$ and the index of the radial power law dependence of the disk emissivity to 3. Then we fit the five XIS spectra simultaneously, imposing only the same disk inclination angle (which was let free to vary) for the 5 observations. All the other parameters (Laor model inner radius and normalization, power law photon index and normalization) were independent from one observation to the other and free to vary. The fit gives a best fit value of the inclination angle $i = 21 \pm 7$ deg, consistent with past measurements (e.g. M04, Reis et al. 2008). The best fit values of the other parameters are reported in Tab. 2 and the contour plots of the disk inclination vs. the disk inner radius are reported in Fig. 5.

The fits are statistically as good as with a gaussian profile, the line flux and equivalent width behaviors being completely consistent between the two profiles. Compared to the gaussian fits, the line energy is now consistent with a constant between the 5 observations and it is significantly higher with a mean value $\langle E_{Laor} \rangle = 6.96 \pm 0.07$ keV. Concerning the disk inner radius, it is well constrained to a few Schwarzschild radii for OBS1 and OBS2 while we have only upper limits for the three last observations. While it strongly suggests the presence of the accretion disk very close to the black hole at the beginning of the campaign, the data prevent any clear conclusion concerning the disk recession.

3.2.2. 0.7-10 keV: XIS data alone

We now include the 0.7-3 keV data in the fitting procedure. The ratios data/model of the five XIS spectra obtained after extrapolation of the best fit POWER LAW + LAOR model down to 0.7 keV are plotted in Fig. 6. A photo-electric

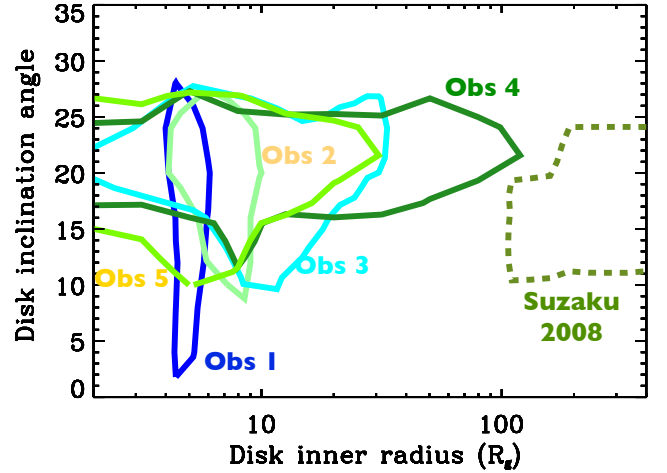


Fig. 5. The 90% contour plots of the disk inclination angle vs. disk inner radius obtained by fitting simultaneously the five XIS spectra with a power law + Laor model above 3 keV. We impose the same inclination angle between the 5 models. The dashed contour corresponds to the Suzaku observation of 2008 (Tomsick et al., 2009)

absorption (model TBNEW⁹ in XSPEC) was added but the Hydrogen column density was fixed to $6 \times 10^{21} \text{ cm}^2$ i.e. the typical galactic N_H observed in the direction of GX 339-4 (e.g. Zdziarski et al. 2004; Cadolle Bel et al. 2011). The soft X-ray part of the spectra varies in time, in excess above the power law extrapolation in OBS1 and OBS2, but in deficit in the three last observations. Letting the column density free to vary improves the fits, but they are still statistically unacceptable especially in the case of OBS1 and OBS2.

The soft X-ray excess could be the signature of the optically thick accretion disk component which dominates the X-ray emission in the soft state, then smoothly disappearing from OBS1 to OBS5 when the source re-enters

⁹ All modeling was performed using the "wilm" abundances (Wilms, Allen & McCray 2000) with the vern cross-sections (Verner et al. 1996)

Obs.	Γ	<i>power law</i>			χ^2/dof	
		$F_{3-10 \text{ keV}}$ ($\times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$L_{3-10 \text{ keV}}/L_{Edd}$ (%)			
1	1.72 \pm 0.01	3.35	0.188		429/254	
2	1.56 \pm 0.01	2.05	0.115		303/254	
3	1.53 \pm 0.02	0.89	0.050		297/251	
4	1.53 \pm 0.02	0.66	0.037		314/245	
5	1.57 \pm 0.02	0.47	0.026		220/219	
2008	1.52 \pm 0.01	0.44	0.024		435/254	
<i>power law+gauss</i>						
Obs.	Γ	E_{gauss} (keV)	σ_{gauss} (keV)	F_{gauss} ($\times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$)	EW (eV)	χ^2/dof
1	1.81 \pm 0.02	6.40 \pm 0.10	0.66 \pm 0.13	6.5 $^{+1.7}_{-1.4}$	150 $^{+40}_{-35}$	285/251
2	1.60 \pm 0.02	6.49 \pm 0.12	0.35 \pm 0.13	1.5 $^{+0.6}_{-0.5}$	55 $^{+25}_{-20}$	267/251
3	1.57 \pm 0.02	6.77 \pm 0.13	0.36 \pm 0.11	1.0 $^{+0.4}_{-0.4}$	90 $^{+35}_{-35}$	263/248
4	1.56 \pm 0.03	6.42 \pm 0.20	0.36 \pm 0.22	0.5 $^{+0.4}_{-0.3}$	60 $^{+35}_{-35}$	300/242
5	1.62 \pm 0.06	6.59 \pm 0.30	0.60 \pm 0.51	0.7 $^{+1.4}_{-0.4}$	130 $^{+75}_{-105}$	207/216
2008	1.54 \pm 0.01	6.41 \pm 0.02	0.10 \pm 0.03	0.4 $^{+0.1}_{-0.1}$	65 $^{+10}_{-10}$	248/251
<i>power law+laor</i>						
Obs.	Γ	E_{laor} (keV)	R_{in} (R_g)	F_{laor} ($\times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$)	EW (eV)	χ^2/dof
1	1.80 $^{+0.02}_{-0.01}$	7.00 $^{+0.13}_{-0.08}$	5.0 $^{+0.5}_{-0.6}$	6.0 $^{+1.1}_{-0.9}$	160 $^{+40}_{-30}$	286/250
2	1.60 $^{+0.02}_{-0.02}$	6.84 $^{+0.12}_{-0.14}$	6.3 $^{+2.7}_{-1.3}$	1.9 $^{+0.6}_{-0.3}$	80 $^{+40}_{-30}$	266/250
3	1.58 $^{+0.03}_{-0.03}$	7.06 $^{+0.16}_{-0.13}$	<35	1.3 $^{+0.5}_{-0.7}$	140 $^{+60}_{-60}$	260/247
4	1.56 $^{+0.03}_{-0.03}$	6.82 $^{+0.22}_{-0.48}$	<180	0.7 $^{+0.4}_{-0.4}$	90 $^{+60}_{-70}$	300/241
5	1.61 $^{+0.06}_{-0.02}$	7.03 $^{+0.38}_{-0.19}$	<25	0.7 $^{+0.6}_{-0.2}$	120 $^{+130}_{-90}$	207/215
2008	1.54 $^{+0.01}_{-0.01}$	6.43 $^{+0.02}_{-0.02}$	>100	0.38 $^{+0.05}_{-0.04}$	65 $^{+5}_{-5}$	248/251

Table 2. Best fit of the XIS data between 3 and 10 keV with a simple power law, a power-law + gaussian line and a power-law + Laor profile emission line. In the last case, the 5 XIS spectra have been fitted simultaneously, letting all the parameters free to vary but imposing the Laor profile inclination angle to be the same between the 5 models. The best fit value for the inclination angle is $i=21^{+5}_{-7}$ deg. The errors on the inner disk radius R_{in} of the Laor profile correspond to a confidence level of 90% for 2 parameters. We have reported also the best fit parameter values for the 2008 Suzaku observation, again assuming the same inclination angle than the 5 other Suzaku observations. With the addition of these data, the best fit value for the inclination angle then becomes $i = 20^{+3}_{-6}$ deg. To compute the 3-10 keV flux in Eddington unit, we adopt an Eddington luminosity of $L_{\text{Edd}} \simeq 1.3 \times 10^{39} \text{ erg s}^{-1}$ (i.e. we assume a 10 solar masses black hole) and a distance to GX 339-4 of 8 kpc.

in the hard state. To test this hypothesis, we have added a multicolor disk component DISKBB in our fits. The column density is still free to vary independently for the 5 observations¹⁰. The best fit parameters are reported in Tab. 3. The addition of a multicolor disk component improves strongly the fit of OBS1 and OBS2 with $\Delta\chi^2=1332$ and 173 respectively. This component is not statistically required however in the three last observations potentially suggesting the disappearance of the disk component during the state transition.

We have reported on Fig. 7 the contour plots, for the 5 observations, of the DISKBB normalization vs. $R_{\text{in},\text{laor}}$ the best fit value of the inner disk radius of the LAOR profile. Assuming an inclination angle of 21 deg., a distance of 8 kpc and a black hole mass of 10 solar masses, the DISKBB normalizations can also be converted to an "apparent" disk inner radii $R_{\text{in},\text{app}}$.

¹⁰ Imposing N_h to the same value for the 5 observations give a much worse fit with $\Delta\chi^2=171$ for 4 less dof.

Taking into account a color temperature correction factor $f_{\text{col}} = 1.7$ (Shimura & Takahara, 1995; Kubota et al., 1998; Davis et al., 2006; Done et al., 2012), we deduce the "true" inner radius $R_{\text{in},\text{diskbb}} = f_{\text{col}}^2 R_{\text{in},\text{app}}$. The values of $R_{\text{in},\text{diskbb}}$ have been reported on the right axis of Fig. 7a.

Both estimates of the disk inner radius (i.e. from DISKBB or LAOR) roughly agree one with each other. Note a few differences however: $R_{\text{in},\text{laor}}$ are consistent between OBS1 and OBS2 while $R_{\text{in},\text{diskbb}}$ of OBS1 is smaller and inconsistent with the OBS2 value. In both cases however, the inner radius is found to be lower than or of the order of 10 R_g . In OBS3 $R_{\text{in},\text{laor}}$ is constrained to be in between ~ 5 and $\sim 40 R_g$ while $R_{\text{in},\text{diskbb}}$ is unconstrained. In OBS5 $R_{\text{in},\text{laor}}$ is upper limited to $\sim 50 R_g$ while $R_{\text{in},\text{diskbb}}$ is unconstrained. We reach however the same conclusions for the evolution of the disk inner radius, R_{in} being small in OBS1 and OBS2 ($< 10 R_g$), but then the contours for OBS3, OBS4 and OBS5 becomes too large to constrain its

Obs.	<i>tbnew</i> *(<i>diskbb</i> + <i>power law</i> + <i>laor</i>)									
	N_h $\times 10^{22}$	T_{in} (eV)	N_{diskbb} $\times 10^3$	Γ	E_{laor} (keV)	$R_{in,laor}$ (R_g)	F_{laor} $\times 10^{-4}$	EW (eV)	χ^2/dof	$\Delta\chi^2$
1	$0.47^{+0.01}_{-0.01}$	330^{+10}_{-10}	$1.0^{+0.2}_{-0.2}$	$1.84^{+0.02}_{-0.01}$	$7.04^{+0.06}_{-0.07}$	$5.0^{+0.9}_{-0.5}$	$5.9^{+1.0}_{-0.9}$	160^{+30}_{-30}	593/384	1332
2	$0.63^{+0.04}_{-0.03}$	210^{+10}_{-10}	$5.3^{+2.8}_{-1.9}$	$1.69^{+0.02}_{-0.01}$	$6.89^{+0.12}_{-0.09}$	$6.8^{+2.3}_{-1.6}$	$2.1^{+0.7}_{-0.5}$	80^{+30}_{-30}	441/384	173
3	$0.57^{+0.10}_{-0.02}$	<160	>10.0	$1.61^{+0.03}_{-0.03}$	$7.07^{+0.15}_{-0.24}$	$8.2^{+24.4}_{-3.0}$	$1.2^{+0.5}_{-0.5}$	110^{+40}_{-40}	386/381	6
4	$0.59^{+0.04}_{-0.05}$	210^{+10}_{-10}	$5.3^{+2.8}_{-1.9}$	$1.69^{+0.02}_{-0.01}$	$6.89^{+0.12}_{-0.09}$	$6.8^{+2.3}_{-1.6}$	$2.1^{+0.7}_{-0.5}$	80^{+30}_{-30}	423/374	7
5	$0.67^{+0.03}_{-0.04}$	$< 8 \times 10^3$	<0.3	$1.63^{+0.20}_{-0.10}$	$7.17^{+0.27}_{-0.47}$	<30	$0.7^{+0.4}_{-0.5}$	130^{+120}_{-90}	358/340	0
2008	$0.51^{+0.01}_{-0.01}$	60^{+20}_{-20}	$<3.9 \times 10^8$	$1.62^{+0.01}_{-0.01}$	$6.44^{+0.02}_{-0.02}$	>210	$0.4^{+0.1}_{-0.1}$	70^{+10}_{-10}	408/384	19

Table 3. Best fit of the XIS data between 0.7 and 10 keV with a diskbb + power-law + Laor line and a photo-electric absorption (model TBNEW, Wilms et al. 2000). The line flux is in units of $\text{ph cm}^{-2} \text{s}^{-1}$. We assume a 10 solar masses black hole for R_g . We report also the $\Delta\chi^2$ fit improvement due to the addition of the multicolor disk component.

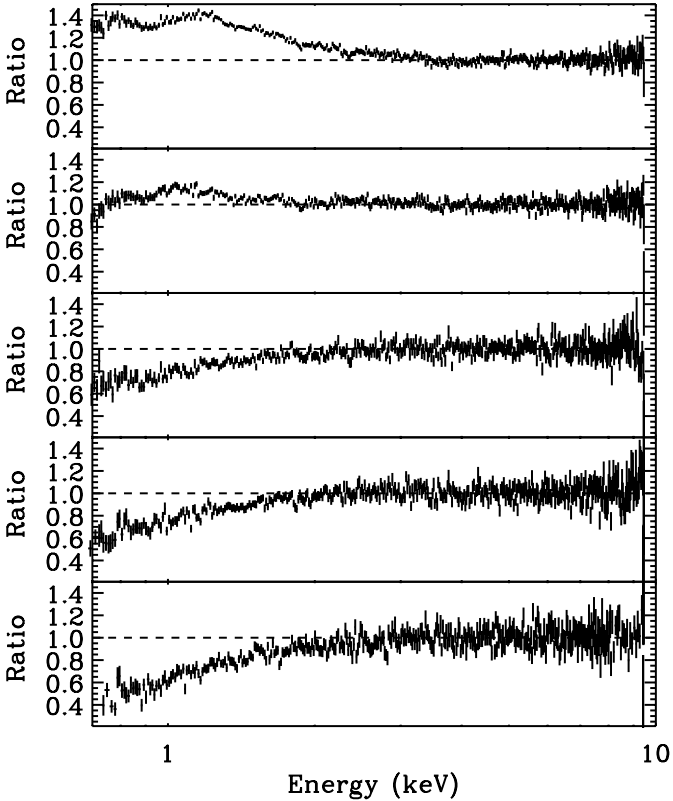


Fig. 6. Ratios data/model of the five XIS0+XIS3 spectra for OBS1 (top) to OBS5 (bottom). The model is a POWER LAW + LAOR fitted above 3 keV and then extrapolated down to 0.7 keV. The Hydrogen column density is fixed to $6 \times 10^{21} \text{cm}^{-2}$. We use TBNEW to model the X-ray absorption (Wilms et al., 2000).

behavior.

We have checked that these results do not significantly change when using a more physical model (via e.g. up-scattering of disk photons) for the high energy continuum like COMPTT in XSPEC. Such models indeed differ to a power-law shape especially in the low energy portion of the spectrum where a low energy roll-over is expected. The corresponding contour plots obtained when fitting with

COMPTT are reported in Fig. 7b. The main differences with Fig. 7a are larger upper limits on $R_{in,laor}$ in OBS4 and OBS5.

Note that the fits reported in Tab. 3 are relatively bad especially for OBS1 and indeed residuals are visible in the soft part ($< 2 \text{ keV}$, see Fig. 9 and 10) of the spectrum indicating that a multicolor disk component alone does not fit the data correctly.

In Fig. 8, we have reported our best fit results with those obtained by Dinçer et al. (2012). These authors use the RXTE/PCA data during the same outburst decay (from MJD 55559.58 to MJD 55649.64). They used also a DISKBB + POWER LAW model, as well as neutral absorption (due to their limited band pass at low energy, they fixed the hydrogen column density at $5 \times 10^{21} \text{cm}^{-2}$)¹¹ so that our results can be safely compared to theirs. As can be seen on Fig. 8, both best fits parameter values agree very well one with each other. Compared to RXTE however, the lower limit of the energy band of the XIS suzaku instrument allows to follow the disappearance of the DISKBB component down to lower flux and lower inner disk temperature.

3.2.3. Comparison with the 2008 Suzaku observation

GX 339-4 was observed by Suzaku in 2008 during a long exposure where flux and spectral index values were very close to the one of OBS5 (Tomsick et al. 2009, T09 hereafter). It is worth noting however that this observation was made 1.6 years after the peak of its 2007 outburst and that the source was in a persistent, but faint, hard state (e.g. Russell et al. 2008; Kong 2008). In comparison, in 2011 GX 339-4 turned back in the hard state since ~ 1 month, when OBS5 was made, and the source flux was clearly in the decreasing phase of the end of the outburst.

The long exposure (the combined XIS0+XIS3 exposure time is of the order of 210 ks) results in a high statistics compared to our own observations. From the fit of the iron line profile, T09 showed that the data agreed with a truncated accretion disk with $R_{in} > 30R_g$ at 90% confidence for a disk inclination of 0 deg, and $R_{in} > 70R_g$

¹¹ They also added a smeared edge at a fixed energy of 10 keV to fit the iron K absorption edge seen around 7.1 keV.

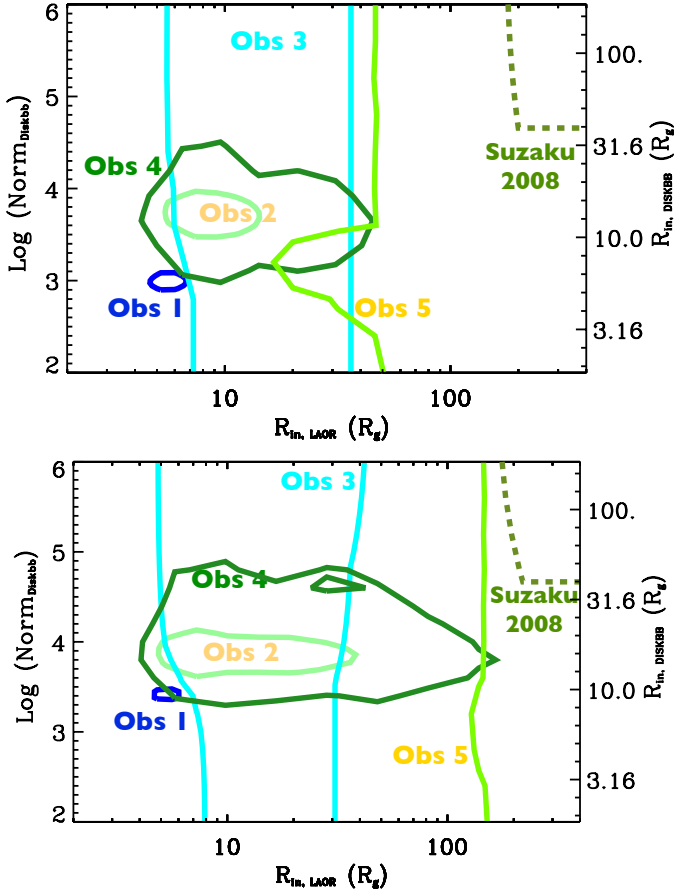


Fig. 7. Contour plots of the disk normalization (left scale) and the corresponding disk inner radius $R_{in,diskbb}$ (right scale) vs. the disk inner radius $R_{in,laor}$ deduced from the LAOR profile. The five XIS spectra have been fitted with a DISKBB + LAOR model and a POWER LAW (top) or a comptonization model COMPTT (bottom) for the continuum. We assume a disk inclination of 20 deg., a distance of 8 kpc and a black hole mass of 10 solar masses. For OBS5, the 90% confidence area is on the left of the yellow line. The dashed contour corresponds to the Suzaku observation of 2008 (Tomsick et al., 2009).

for a disk inclination of 20 deg.

We have re-analyzed these data following the procedure detailed in Sect. 2. We have fitted them in the 3-10 keV energy range with the POWER LAW + GAU model first. The corresponding contour plots of the line flux and line width versus line energy are overplotted in Fig. 4 and the best fit parameter values are reported in Tab. 2. If the spectral shape and flux are in good agreement with OBS5, the line width is clearly inconsistent between the two observations, indicating intrinsic differences (geometry? ionisation state?) of the reflecting material.

Then we have fitted these data, still in the 3-10 keV energy range, but with the POWER LAW + LAOR model, either separately or simultaneously to our 5 Suzaku pointings, imposing, in the latter case, the inclination angle to the same value for each data set. The best fit results are very similar in both cases and are in agreement

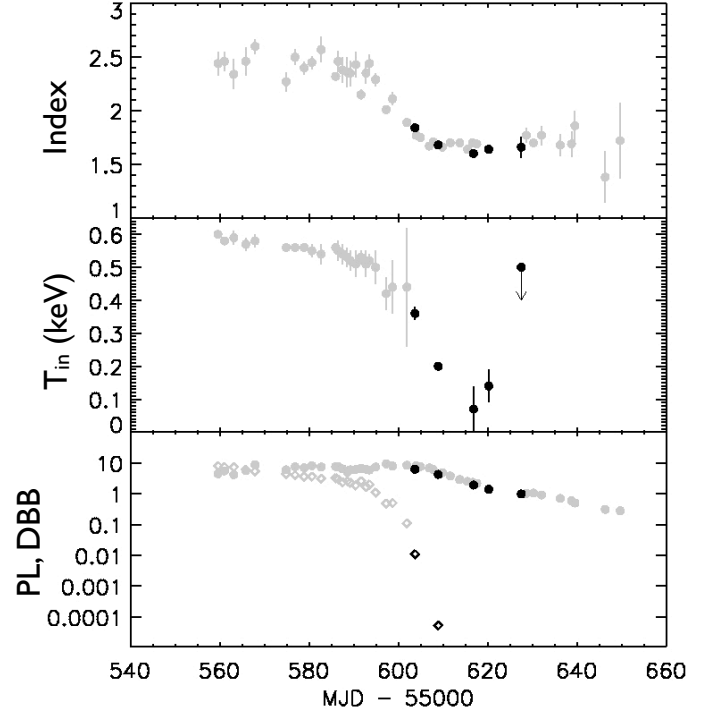


Fig. 8. Evolution of the power law photon index (top), the inner disk temperature T_{in} (middle) and the power-law and disk flux (bottom, filled and empty circles respectively) in the 3-25 keV energy band in units of 10^{-10} erg cm $^{-2}$ s $^{-1}$. The black symbols are the results of this campaign while the gray ones have been obtained by Dinger et al. (2012). The model used is TBNEW × (DISKBB + POWER LAW + GAUSSIAN) in the 0.7 - 10 keV range.

with those of T09 (see last row of Tab. 2). We find for 2008 an inner radius $> 100 R_g$ and a best fit inclination angle $i = 20^{+3}_{-6}$ degrees consistent with our previous value obtained without the use of these data (see Sect. 3.2.1). We have overplotted the 90% contour plot of the disk inclination angle vs. disk inner radius of the 2008 observation in dashed line in Fig. 5. **While only at a 2σ level, the fact that it does not overlap with the 90% contours obtained for our 2011 observations strongly suggests that the constraints on the disk inner radius deduced from the LAOR model are inconsistent between 2008 and 2011.**

Following the fitting procedure of the previous sections, we have also fitted the 2008 data set in the 0.7-10 keV range adding now a DISKBB component to the model. The best fit results are reported in the last row of Tab. 3 and the corresponding contour plots of the DISKBB normalization vs. inner disk radius have been overplotted in dashed line in Fig. 7. The constraints on R_{in} deduced from the DISKBB normalization give now a lower limit of $\sim 30 R_g$ (to be compared with the lower limit of $\sim 200 R_g$ from the *Laor* fit of the iron line), in agreement with our (unconstrained) contour plots of OBS3 and OBS5. These constraints on R_{in} from the DISKBB component have to be taken with caution however given that the disk component is poorly constrained in these observations.

<i>tbnew*(diskbb+po+kdblur*reflionx)</i>												
Obs.	N_h $\times 10^{22}$	T_{diskbb} eV	N_{diskbb} $\times 10^4$	F_{diskbb} $\times 10^{-11}$	Γ	F_{po} $\times 10^{-10}$	R_{in}	ξ_{ref} R_g	F_{ref}	$\frac{L_{bol}}{L_{Edd}}$ $\times 10^{-11}$	χ^2/dof %	
1	$0.42^{+0.01}_{-0.01}$	430^{+20}_{-20}	$0.03^{+0.01}_{-0.01}$	11.8	$1.73^{+0.01}_{-0.01}$	13.7	15^{+30}_{-5}	1000^{+200}_{-100}	11.3	0.89	806/517	
2	$0.64^{+0.03}_{-0.06}$	220^{+20}_{-10}	$0.33^{+0.28}_{-0.18}$	3.5	$1.67^{+0.01}_{-0.02}$	9.0	40^{+240}_{-25}	230^{+30}_{-15}	11.1	0.56	601/517	
3	$0.67^{+0.09}_{-0.06}$	110^{+30}_{-40}	$6.10^{+216.80}_{-5.10}$	0.4	$1.59^{+0.02}_{-0.03}$	4.0	>70	1100^{+800}_{-400}	3.8	0.25	522/514	
4	$0.75^{+0.07}_{-0.06}$	125^{+20}_{-30}	$1.84^{+5.81}_{-1.31}$	0.4	$1.63^{+0.02}_{-0.03}$	3.0	>10	790^{+5700}_{-600}	2.1	0.20	554/507	
5	$0.82^{+0.25}_{-0.13}$	<240	< 2.13	<2.6	$1.63^{+0.04}_{-0.18}$	2.1	>30	1400^{+3900}_{-1100}	2.0	0.13	483/476	
2008	$0.79^{+0.02}_{-0.02}$	80^{+20}_{-20}	$64.64^{+960.70}_{-57.09}$	0.1	$1.65^{+0.01}_{-0.01}$	1.9	>180	20^{+30}_{-10}	3.0	0.13	527/517	
<i>tbnew*(diskbb+eqpair+kdblur*reflionx)</i>												
Obs.	N_h $\times 10^{22}$	T_{diskbb} eV	F_{diskbb} $\times 10^{-11}$	l_h/l_s	τ	T_{bb} eV	F_{eqpair} $\times 10^{-10}$	R_{in} R_g	ξ_{ref}	F_{ref} $\times 10^{-11}$	$\frac{L_{bol}}{L_{Edd}}$ %	χ^2/dof
1	$0.46^{+0.01}_{-0.01}$	310^{+10}_{-10}	16.0	$5.1^{+0.2}_{-0.1}$	$0.6^{+0.3}_{-0.3}$	590^{+10}_{-30}	11.9	$7.0^{+1.1}_{-1.3}$	2000^{+100}_{-200}	28.8	0.91	704/515
2	$0.62^{+0.07}_{-0.06}$	240^{+10}_{-20}	7.0	$5.7^{+0.3}_{-0.1}$	$2.3^{+0.1}_{-0.1}$	470^{+20}_{-20}	9.3	32^{+33}_{-19}	270^{+185}_{-70}	7.8	0.60	544/515
3	$0.75^{+0.03}_{-0.03}$	110^{+30}_{-30}	0.8	$9.6^{+1.9}_{-2.1}$	$2.1^{+1.6}_{-1.4}$	210^{+50}_{-95}	4.0	>70	1180^{+480}_{-480}	4.6	0.25	519/512
4	$0.78^{+0.08}_{-0.25}$	175^{+100}_{-40}	1.3	$6.4^{+0.5}_{-0.5}$	$2.4^{+2.2}_{-0.2}$	390^{+50}_{-100}	3.1	>10	910^{+2100}_{-520}	1.7	0.19	546/505
5	$0.93^{+0.15}_{-0.14}$	130^{+30}_{-40}	0.7	$7.7^{+4.0}_{-0.6}$	$1.9^{+2.0}_{-1.4}$	240^{+60}_{-60}	2.1	>30	1450^{+3590}_{-1150}	2.3	0.13	475/474
2008	$0.84^{+0.03}_{-0.03}$	80^{+10}_{-10}	0.2	$7.9^{+0.5}_{-0.4}$	$2.1^{+0.6}_{-0.2}$	190^{+20}_{-30}	2.0	>180	40^{+15}_{-20}	3.2	0.13	525/515

Table 4. Results of the fits of the XIS and HXD data with a POWER LAW (top table) or EQPAIR (bottom table) for the continuum and the ionized reflection component REFLIONX. **In the case of the POWER LAW fit, the photon index used in REFLIONX is fixed to the one of the power law continuum. In the case of EQPAIR, we froze the photon index of REFLIONX to the one obtained in the power law fit.** The inclination was fixed to 20 deg. We uses the kernel from the LAOR line profile to account for the gravitational effects close to the black hole (model KDBLUR) of XSPEC). All errors are 90 per cent confidence for one parameter. The fluxes are in unit of $\text{ergs.cm}^{-2}.\text{s}^{-1}$ and are computed in the 0.7-70 keV energy range. The bolometric luminosity L_{bol} is assumed to be the sum of the luminosities of the three spectral component DISKBB, EQPAIR and REFLIONX. We adopt an Eddington luminosity of $L_{Edd} \simeq 1.3 \times 10^{39} \text{ erg s}^{-1}$ (i.e. we assume a 10 solar masses black hole) and a distance to GX 339-4 of 8 kpc.

3.3. Broad band spectral analysis: ionized reflection

3.3.1. Ionized reflection

From the previous sections, fits of the soft X-ray excess and iron line profiles, independently one with each other, both suggest an increase of the disk inner radius from OBS1 to OBS2. Its evolution is however uncertain for the three last observations. We also confirm the large value of R_{in} deduced from the iron line fit in the 2008 Suzaku observation. To go a bit further, we use, in this section, more realistic models for the continuum and the reflection component. We take also advantage of the HXD instrument of Suzaku and include the HXD/PIN (20-70 keV) data in our fits.

We have reported In Fig. 9 the χ^2 contribution when we extend the best fit model TBNEW \times (DISKBB+ POWER LAW + LAOR) of the XIS data (the best fit parameters are reported in Tab. 3) above 10 keV in the HXD/PIN energy range. A clear excess between 20 and 40 keV is visible especially in OBS1 and OBS2 and suggests the presence of a reflection bump.

To provide a more physical description of the reflection component giving birth to the iron line, we use the combination of the REFLIONX code of Ross & Fabian (2005), convolved with the relativistic kernel KDBLUR (Laor, 1991). In agreement with the results of Sect. 3.2.1, we fix in KDBLUR the outer disk radius R_{out} to $400 R_g$, the index of the radial

power law dependence of the emissivity to 3 and the disk inclination angle to 20 degrees.

In REFLIONX the illumination has a power law shape. So we first fit the different observations with a power-law for the primary continuum, **fixing the photon index in REFLIONX to that of the power law continuum.** However, as already discussed in Sect. 3.2.2, comptonization of the soft disk photons in a hot corona is widely accepted as the mechanism at the origin of the X-ray continuum of X-ray binaries. Thus, instead of a simple power law, we also use the Comptonization model EQPAIR (Coppi, 1999) even if it is not perfectly consistent with the use of REFLIONX. **In this case, we fix the photon index in REFLIONX to the precedent values obtained when fitting with the power law continuum**¹² We will see that our results are qualitatively similar between the two models, the advantage of EQPAIR being that its main parameters (i.e. the ratio between the compactness of seed photons, l_s , and hot electrons, l_h , the corona optical depth τ and the temperature of the soft disk photons T_{bb}) have a direct physical meaning.

The best fit parameters obtained with these models are reported in Tab. 4. Note that the fits are always better with EQPAIR than with a power law. The lack of a low energy roll-over in this latter case could explain

¹² **The slope of EQPAIR can be estimated from the l_h/l_s ratio (e.g. Malzac et al. 2001) and appears to be very close to the photon index of the power law fits.**

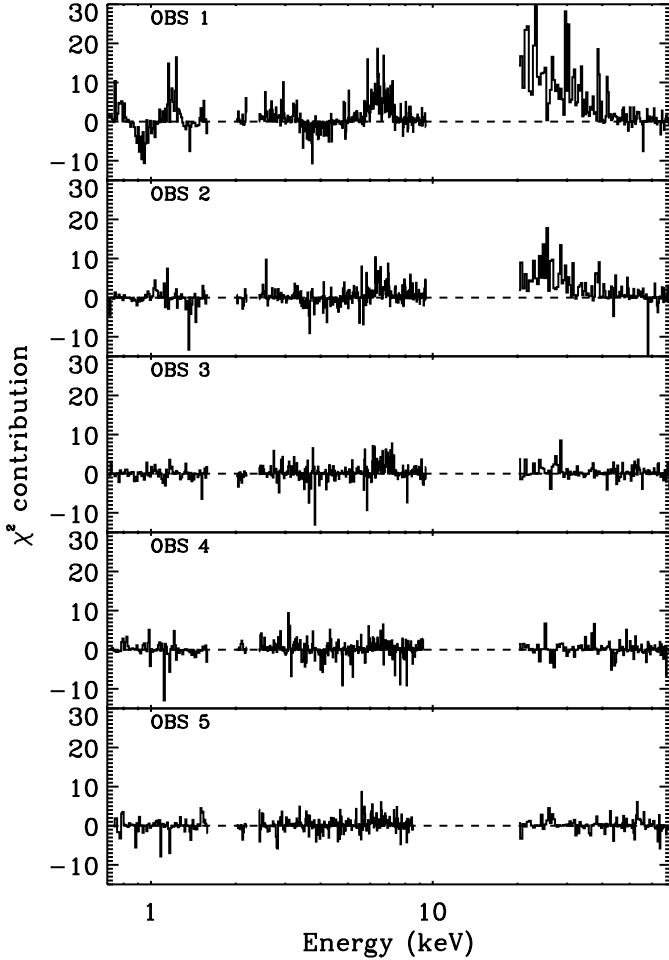


Fig. 9. χ^2 contribution in the 0.7-70 keV range when extending the best fit model TBNEW \times (DISKBB+ POWER LAW + LAOR) (see Tab. 3) of the XIS data above 10 keV in the PIN energy range. The LAOR component has been suppressed in these plots. Strong residuals are visible near 6.4 keV and above 10 keV especially for OBS1 and OBS2.

the larger residuals observed in the soft band (< 2 keV). The best fit parameters are however qualitatively similar between the two models, the main difference being the reflection component in OBS1 which has a lower flux and lower ionization with the use of a power law continuum. But R_{in} is still well constrained to a small value $\sim 15 R_g$ in this observation. Note also that the ionization parameter is not larger in OBS3 compared to the other observations and then does not support the presence of a more ionized iron line as suggested by the fits between 3 and 10 keV with a simple gaussian (see Sect. 3.2.1).

Since both models (with a power law or EQPAIR for the continuum) give similar parameter constraints and since the fits with EQPAIR gives always a better χ^2 , from now on we will only discuss the results obtained with this model. We find good fits in all cases but OBS1 for which some features are still present in the soft energy range (< 1 keV, see next section). The unfolded spectra as well as the data/model ratios of each observation are reported in Fig. 10. In order to make a direct comparison to the DISKBB + POWER LAW + GAUSSIAN fits below 10 keV discussed

in Sect. 3.2.2 (and reported in Tab. 3), we have computed the corresponding χ^2/dof of these new fits but limited to the 0.7-10 keV energy range. We find the following values: 530/382, 401/382, 392/379, 417/372 and 355/341 for the five (from OBS1 to OBS5) observations respectively. The improvement of the fits in the 0.7-10 keV energy range with the blurred ionized reflection model are really significant for OBS1 and OBS2 with $\Delta\chi^2 = 49$ and 27 for two less degrees of freedom. No significant improvement is obtained for the other observations, potentially because of their lower statistics.

The hard to soft compactnesses ratio l_h/l_s increases smoothly all along the monitoring in agreement with the observed spectral hardening (see Tab. 2). It is of the order of 5-8 suggesting a photon starved geometry for the hot corona. On the other hand, the hot corona optical depth, τ , increases significantly between OBS1 and OBS2 by a factor ~ 4 and then stays roughly constant of the order of $\sim 2-3$. Concerning the ionization parameter, apart from OBS2, it is relatively high (with admittedly large error bars) of the order of $\xi_{ref} \sim 1000$, suggesting a ionized reflecting medium.

The 0.7-70 keV fluxes of the different spectral components (respectively F_{diskbb} , F_{eqpair} and F_{ref}) are also reported in Tab. 4. They show a clear decrease along the monitoring in agreement with the fact that the source returns back to its quiescent state. However, the relative ratios F_{diskbb}/F_{eqpair} and F_{ref}/F_{eqpair} are not constant, as we could expect if all the spectral components faded in the same way. These ratios decrease from ~ 14 to 1% and ~ 25 to 10% respectively.

The DISKBB temperature, T_{diskbb} , as well as the EQPAIR soft photon temperature, T_{bb} , show also clear decrease from OBS1 to OBS5. Interestingly, while the two temperatures were let free to vary during the fitting procedure, T_{diskbb} is about half T_{bb} (see Fig. 11a). Such correlation may have a physical origin. Indeed, in EQPAIR the soft temperature T_{bb} corresponds to the disk temperature actually "see" by the hot corona. On the other hand, T_{diskbb} is the effective disk temperature. The ratio between the two, the so-called spectral hardening factor, is generally estimated to be of the order of 2-3 (e.g. Shimura & Takahara 1995; Sobczak et al. 1999; Merloni et al. 2000; Davis et al. 2006) in agreement with what we find.

For comparison we have also fitted the 2008 Suzaku observation with the same model. The best fit parameters are reported in the last row of Tab. 4. Interestingly, apart from the reflection ionization parameter which is of the order of ~ 40 i.e. well below our best fit values observed in 201 and a larger disk inner radius, the other parameters agree well with the spectral evolution from OBS1 to OBS5. More precisely, and even if there is a 3 year gap between them as well as a poorer statistics in 2011, the 2008 observation seems to be very similar to OBS5 but with a different accretion disk state.

We have checked if the uncertainties on R_{in} in OBS5 could be due to the lower statistics compared to 2008 by simulating a set of data from the best fit model obtained for 2008 but with a combined XIS0+XIS3 exposure time of 40

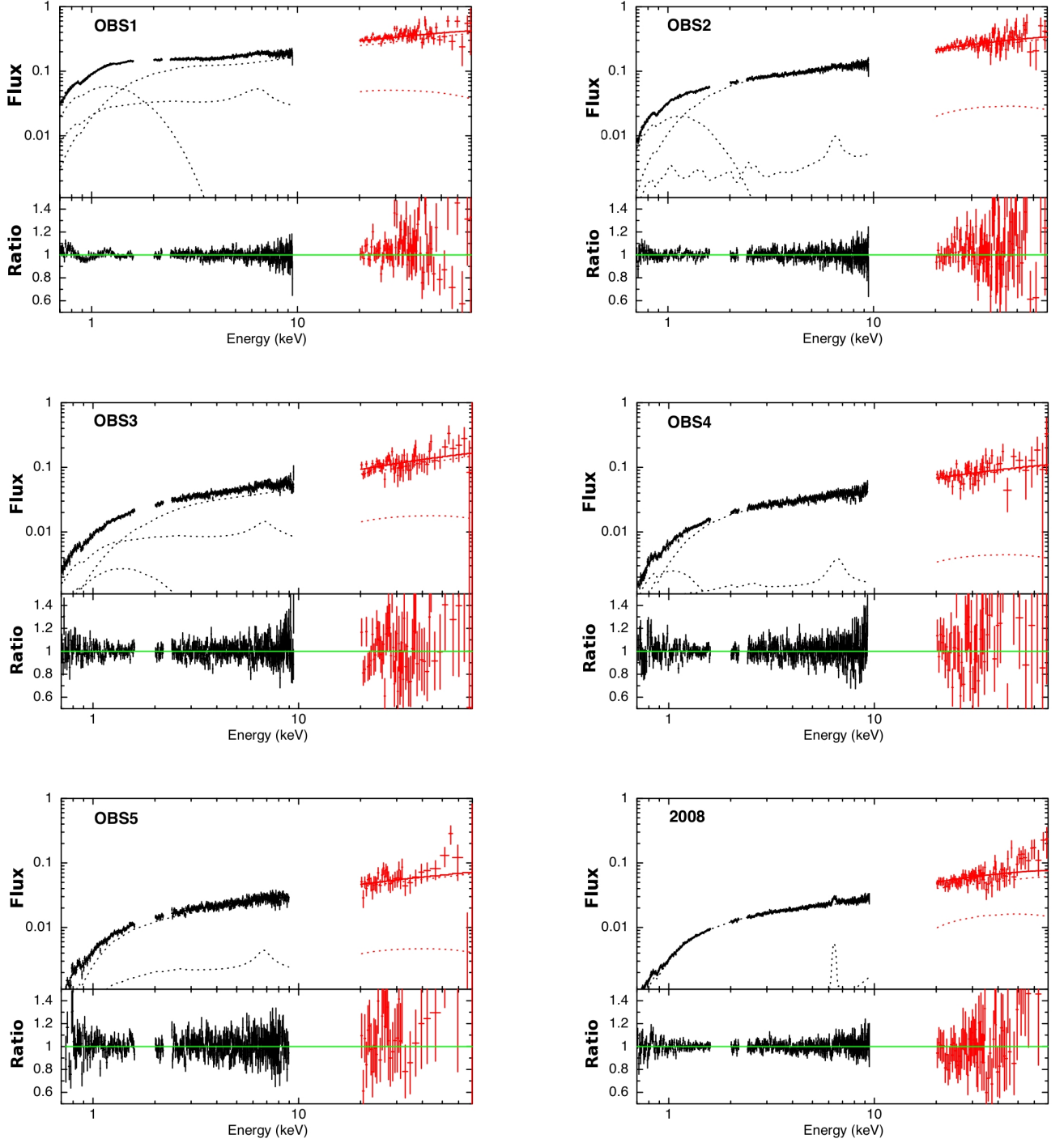


Fig. 10. Unfolded best-fit model of the five Suzaku observations (XIS: black crosses; HXD/PIN: red crosses) and corresponding data/model ratios using EQPAIR for the continuum, a blurred reflection KDBLUR \otimes REFLIONX for the reflection component and a multicolor disk DISKBB for the soft X-rays.

ks (i.e. of the order of the exposure time of OBS5) instead of 210 ks. A fit of this simulated spectrum gives $R_{in} > 130R_g$ and $\xi_{ref} = 70^{+60}_{-20}$. So if the OBS5 spectrum and line shape were exactly the same as in 2008, we should have obtained values of R_{in} and ξ_{ref} in agreement with those observed in 2008, even if the statistics of OBS5 is low. This is in contradiction with our results and this suggests that the

accretion disk is in an intrinsically different state between 2008 and 2011.

3.3.2. Ionized absorption

As said previously, the best fit of OBS1 is not very satisfactory and features are visible, especially in the soft X-ray range, in the data/model ratio reported in Fig. 10.

The presence of absorption lines in the soft X-ray spectrum of GX 339-4 have already been reported in the literature when the source was in an intermediate state transiting to the low/hard state (e.g. M04, Juett et al. 2006). If most of these lines may be produced by the Interstellar Medium (Juett et al., 2006), a sizable contribution of a few of them (like e.g. the Ne IX line at 0.922 keV) could be due to a local contribution from an intrinsic AGN-like warm-absorber perhaps produced by a disk wind.

We have tested the presence of such absorber by adding an ionized absorber component (model ABSORI of XSPEC) in our fits. The fit of OBS1 improves significantly ($\Delta\chi^2=102!$) thanks to the addition of this spectral component. The corresponding parameters of the absorber are reported in Tab. 5 i.e. an hydrogen column density of $N_{h,abs} \sim 10^{22}\text{cm}^{-2}$ and an ionization parameter $\xi_{abs} \sim 300$. The other model parameters do not significantly change compared to Tab. 4. We add the same ABSORI component to the other observations (including 2008). We do not find any significant improvement. The best fit are also reported in Tab. 5. The decrease of the signal-to-noise ratio may however limit the correct detection of absorbing material¹³.

Then, we can have a rough estimate of the maximal distance d between the absorbing material and the X-ray source by assuming that d is necessarily larger than the radial extension Δr of the absorber. Since $N_{h,abs} = n\Delta r$ (n being the density of the warm absorber) and $\xi_{abs} = \frac{L_{bol}}{d^2 n}$ then $d > \Delta r$ implies $d < \frac{L_{bol}}{\xi_{abs} N_{h,abs}}$. Using the best fit parameter values obtained for OBS1 i.e. $L_{bol} \simeq 10^{37} \text{ erg s}^{-1}$, $\xi_{abs} \simeq 300 \text{ erg cm s}^{-1}$ and $N_{h,abs} \simeq 10^{22}\text{cm}^{-2}$ we find that the absorber should be at a maximal distance of $\sim 10^6 R_g$ (assuming a 10 black hole solar masses) from the central X-ray source. **This is of the order of the binary separation in GX 339-4 as estimated by Zdziarski et al. (2004), thus agreeing with the fact that the absorber may be produced in the inner parts of the binary system.**

To have a qualitative idea of the ions potentially responsible for the observed absorption features in OBS1, instead of ABSORI we simply add gaussian absorption lines, with width fixed to 0 eV (a more detailed work on these absorption line is dedicated to a future work). We focus only on OBS1 since the other observations do not need apparently the addition of absorption components. As previously said, a few absorption lines were already observed in GX 339-4 in past Chandra observations (M04), the most intense one being Ne IX at 0.922 keV. We thus add an absorption gaussian line with energy in the range 0.9-0.95 keV. The fit improves strongly with $\Delta\chi^2=61$ for 3 less degrees of freedom. The gaussian best fit energy

¹³ Note that, despite the difference in the the soft band due to the lack of a low energy roll-over when fitting the continuum with a power law, we obtain consistent values of the absorber parameters when we use this model instead of EQPAIR

Obs.	<i>Ionized absorber</i>			
	N_h $\times 10^{22}$	ξ_{abs}	$\Delta\chi^2$	χ^2/dof
1	$1.0^{+0.2}_{-0.2}$	320^{+90}_{-60}	107	597/513
2	$0.4^{+0.1}_{-0.3}$	180^{+230}_{-130}	3	541/513
3	<4.0	>90	-1	520/510
4	<2.4	$[0 - 5000]$	1	551/503
5	$7.4^{+3.2}_{-3.7}$	>4900	3	472/472
2008	<0.25	$[0 - 5000]$	0	524/513

Table 5. Best fit parameters of the ionized absorber component. The $\Delta\chi^2$ is the χ^2 variation compared to the best fits reported in Tab. 4

$E_{abs}=0.92\pm 0.02$ is consistent with Ne IX¹⁴. The line has an equivalent width (EW) of ~ 5.7 eV which corresponds to a Neon column density in between 5×10^{16} and 10^{17} cm^{-2} (see M04 for the computation of the Neon column density). This agrees completely with the estimates measured by M04 and Juett et al. (2006) and this is still higher than the expected value from the ISM, suggesting also an origin in the local environment of the X-ray binary. **Luo & Fang (2014) reach the same conclusion for GX 339-4 as well as for a sample of 11 other X-ray binaries.** We have tested that the addition of such gaussian absorption line is not needed in the other observations.

We have also tested the presence of (weak) blue-shifted ionized absorption lines from Fe XXV and Fe XXVI since they have been observed in a few microquasars and interpreted as signature of fast ionized outflows. Their expected EW are generally of the order of 10-20 eV (e.g. Ponti et al. 2012). We do not detect such components in our data and find only upper limit for their equivalent width of 5-10 eV.

4. Hints of disk recession

To be correct, when we talk about disk recession, we are talking about the recession of the optically thick part of the accretion flow. It is possible that the accretion disk extends down to the inner more stable orbit but that, for different reasons (e.g. most of its accretion power is advected or ejected), it does not radiate any more.

While we do not find clear indications of disk recession during our monitoring, a few arguments are consistent with this interpretation. First, and contrary to fits below 10 keV, fits of the broad band spectra with blurred ionized reflection give good constraints on R_{in} for OBS1 and OBS2, of the order of $10 R_g$ and $\sim 30 R_g$ respectively, but it also puts lower limits for OBS3 ($> 70 R_g$), OBS4 ($> 10 R_g$) and OBS5 ($> 30 R_g$). For the 2008 data set, our fit gives a lower limit $R_{in} > 180 R_g$, in agreement with T09 and clearly suggesting a disk recession (**but see Fabian et al. (2014) for the limitations of the use of X-ray reflection to estimates the disk inner radius**). The fact that this recession was apparently stronger in 2008 could be due to the

¹⁴ Note that this absorption line energy is well below the Si edge which is known to contaminate the XIS response around 1.8 keV

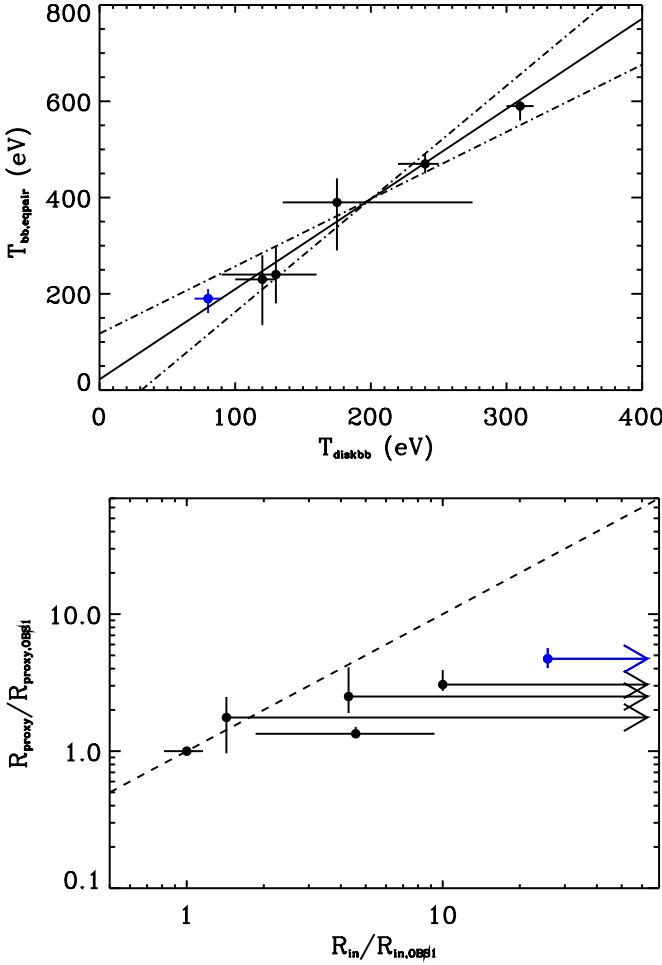


Fig. 11. a) Best fit DISKBB temperature vs EQPAIR soft photon temperature. The solid line is the linear best fit. It has a slope of 1.9. The dot-dashed lines correspond to the 1σ error on the slope i.e. 1.9 ± 0.5 . b) Flux of the DISKBB component versus DISKBB temperature. The black solid line corresponds to the log-log linear best fit $F_{\text{diskbb}} \propto T_{\text{diskbb}}^{3.3}$ and the dot-dashed lines to the 1σ . The red solid line corresponds to the best fit assuming a T_{diskbb}^4 law. c) Plots of R_{proxy} (see Sect. 4) versus the disk inner radius R_{in} deduced from our fits (reported in Tab. 4) and assuming the X-ray luminosity $\propto \dot{M}^\alpha$ with $\alpha=2.5$ (the results are very similar for $\alpha=2$ or 3). The dashed line corresponds to $R_{\text{proxy}} = R_{\text{in}}$. The blue points in each figure correspond to the 2008 Suzaku observation.

fact that the source was in a persistently faint hard state since months. This could have let enough time for the inner accretion flow to evolve into the observed configuration.

Our estimates of l_h/l_s from our fits also agree with the work of Sobolewska et al. (2011). Note however that we are not using exactly the same model as these authors. No reflection component was taken into account in their work but an iron line. We do not expect however that this would have any strong effect on our estimate of l_h/l_s compared to their methods given the low flux we found in the reflection component (i.e. a factor 10 below the continuum flux, see Tab. 4). Thus we believe that our results can be safely compared to theirs. These authors studied the changes of the l_h/l_s ratio with the bolometric luminosity L_{bol} in the hard states of GX 339-4 and GRO J1655-40. At luminosities of the order of ~ 0.1 – 1% , i.e. the range of luminosities of the present Suzaku observations, Sobolewska et al. (2011) confirmed a transition in behaviour of l_h/l_s with L_{bol} . At luminosities lower than ~ 0.1 – 1% , both parameters correlate while they anticorrelate at larger L_{bol} . According to these authors, this behavior is consistent with a scenario where seed photons change from cyclo-synchrotron, at the lowest luminosities, to those from a (truncated) disk, at higher luminosities. Our observed increase of l_h/l_s from OBS1 to OBS5, i.e. with a decrease of L_{bol} , suggests then that the emission of the accretion disk is still dominating the cooling process of the

hot corona.

But then, the changes of l_h/l_s implies a variation of the disk-corona geometry. The increase of l_h/l_s from OBS1 to OBS5 indicates a faster decrease of the soft photon flux compared to the corona heating power. This situation is naturally expected if R_{in} increases from OBS1 to OBS5. Note that the increase of R_{in} would also imply a diminution of the reflecting area and consequently a faster decrease of the reflecting component compared to primary one. This is also in agreement with the decrease of $F_{\text{ref}}/F_{\text{eqpair}}$ as discussed in Sect. 3.3.1.

We have reported in Fig. 11b the flux F_{diskbb} of the DISKBB component versus the DISKBB temperature T_{diskbb} . The log-log linear best fit (black solid line in Fig. 11b) gives $F_{\text{diskbb}} \propto T_{\text{diskbb}}^{3.3 \pm 0.2}$ i.e. a bit smoother than the Stefan-Boltzmann law in T^4 expected in the case of an optically thick accretion disk with fixed inner radius. This discrepancy could be explained by a variation of the hardening factor with the disk temperature (e.g. Salvesen et al. 2013). However, we can again interpret this result in term of variation of the disk inner radius. Indeed, in a standard accretion disk of inner radius R_{in} , inner temperature T_{diskbb} and accretion rate \dot{M} we expect:

$$T_{\text{diskbb}}^4 R_{\text{in}}^3 \propto \dot{M}. \quad (1)$$

On the other hand, at the end of the outbursts, X-ray binaries are known to be in a radiatively inefficient state where the X-ray luminosity is proportional to \dot{M}^α with $\alpha \sim 2 - 3$ (e.g. Coriat et al. 2011 and references therein). Then $F_{eqpair}^{1/\alpha}$ can be used as a proxy for the accretion rate of our system. In consequence, the ratio $R_{proxy} = [F_{eqpair}^{1/\alpha}/T_{diskbb}^4]^{1/3}$ should be a proxy of the disk inner radius R_{in} . We have plotted R_{proxy} normalized to its value in OBS1 (and assuming $\alpha = 2.5$) in Fig. 11c versus the best fit inner radius values R_{in} obtained from our broad band fits. While the values of R_{proxy} for the last 4 observations are always larger than the one computed for OBS1, and then supporting the scenario of the recession of the optically thick part of the accretion disk, they are smaller than R_{in} in most cases. This discrepancy may be due to the bad estimate of the disk inner temperature T_{diskbb} from our fits due to the limited energy range of Suzaku in the soft X.

5. Disk-wind to disk-jet transitions?

In the recent context of outflow/wind signatures detection in black hole X-ray binaries (e.g. Miller et al. 2006c; Ponti et al. 2012; Díaz Trigo et al. 2012) and their potential link to the jet evolution during outburst (Miller et al., 2006d; Neilsen & Lee, 2009), the absorption features significantly detected in OBS1 (and only in OBS1) is an interesting results. Let's recall that the re-ignition of the radio emission was detected just before the beginning of our campaign, peaking between OBS1 and OBS2, and interpreted as the beginning of the jet-structure re-building while the source turned back to the hard state (e.g. C13). By analogy with the observation of the evolution between a jet-dominated to a wind-dominated accretion flow during a hard-to-soft transition in GRS 1915+105 (Neilsen & Lee, 2009), our results could correspond to the reverse situation i.e. the evolution from a wind-dominated to a jet-dominated accretion flow during a soft-to-hard transition.

The absorption features in OBS1 agree with the presence of Neon absorption lines, especially from Ne IX and its column density suggests that part of this line could be produced locally. Interestingly, this line was detected in a Chandra observation of GX 339-4 when the source was in an intermediate state transiting to the low/hard state while OBS1 was observed just before the complete state transition back to the hard state. The disappearance of the Ne IX in the other observations of the monitoring could suggest that it is linked to a disk wind only present before the transition to the hard state. The absence of detection of Fe XXV and Fe XXVI however seems to indicate that this wind, if really present in OBS1, is not highly ionized.

6. Concluding remarks

Our Suzaku monitoring of GX 339-4 at the end of its 2010-2011 outburst caught the source during its soft-to-hard state transition. Simultaneous radio-OIR observations showed the recovery of the radio emission and were interpreted as signature of the re-ignition of the compact jets (C13). The onset of the radio emission occurred between OBS1 and OBS2 while the re-flare observed in OIR reached its maximum close to OBS3 and OBS4.

The Suzaku observations show a global fading of the X-ray flux during the monitoring. For the spectral fits, we first use phenomenological models with a simple power law for the continuum. The addition of an iron line is statistically needed in all the observations. Fits with a LAOR profile are statistically equivalent to fits with a gaussian. Simultaneous fits of the 5 observations with a LAOR profile give a disk inclination angle of ~ 20 deg. The constraints on the inner radius agree with $R_{in} < 10R_g$ in OBS1 and OBS2 at 90% confidence level. Due to the lower statistics, these constraints becomes $< 100R_g$, for the 3 last observations.

The presence of a soft X-ray excess, above the 3-10 keV power law extrapolation, is clearly visible in the two first observations and the addition of a multicolor disk component improves statistically the fits. This is not the case for the three last observations. The evolution of the disk component (decrease of its inner temperature and total flux) agrees with a disk recession from OBS1 ($R_{in} \sim 10 R_g$) to OBS2 ($R_{in} \sim 20 R_g$). However, again, due to the low statistics, we cannot confirm this recession for the last observations. A comparison with the very long Suzaku observation of GX 339-4 during a long faint hard state of its 2007-2008 outburst (T09), in a flux state similar to our OBS5, shows a relatively good agreement of the spectral shape between the two observations. The line shape is however inconsistent between the two pointings. In 2008 the source was observed during a persistent, but faint, hard state while in 2011 it was clearly in the decreasing phase of the outburst. It is then possible that the accretion flow had more time to evolve into a truncated accretion disk in 2008 compared to 2011.

The use of a model including blurred ionized reflection and thermal comptonisation continuum gives better fits than the simple POWER LAW + DISKBB model used previously, at least for OBS1 and OBS2. For the other observations both models give similar results. This model give constraints on R_{in} in marginal agreement with a disk recession. Hints of such recession come also from the increase of the l_h/l_s compacity ratio of the hot corona all along the monitoring, and from the deviation of the disk flux to the Stefan law in T^4 . These hints have to be taken with care however given the low statistics and the complexity of the model that may lead to strong degeneracy between parameters.

Finally, signatures of ionized absorption seem to be present at least in OBS1 but absent in the other observations. The radio re-ignition occurring in between OBS1 and OBS2 (see C13), we suggest that, during these two observations, the accretion flow may have transited from a disk wind, an ubiquitous characteristic of soft states, and a jet, signature of the hard states. These absorption features may be the last signature of the disk wind before the transition to a jet-dominated state.

Acknowledgments

The authors thanks the referee for a careful reading of the manuscript and for his/her comments that well improve its quality. POP acknowledges financial support from CNES.

This work is part of the CHAOS project ANR-12-BS05-0009 supported by the french Research National Agency (<http://www.chaos-project.fr>). This research has made use of data obtained from the Suzaku satellite, a collaborative mission between the space agencies of Japan (JAXA) and the USA (NASA).

References

- Barret, D., Olive, J. F., Boirin, L., et al. 2000, *ApJ*, 533, 329
- Belloni, T., Homan, J., Casella, P., et al. 2005, *astro-ph/0504577*
- Blandford, R. D. & Königl, A. 1979, *ApJ*, 232, 34
- Buxton, M. M., Bailyn, C. D., Capelo, H. L., et al. 2012, *AJ*, 143, 130
- Cabanac, C., Fender, R. P., Dunn, R. J. H., & Koering, E. G. 2009, *ArXiv e-prints*
- Cadotte Bel, M., Rodriguez, J., D’Avanzo, P., et al. 2011, *A&A*, 534, A119
- Coppi, P. S. 1999, in *Astronomical Society of the Pacific Conference Series*, Vol. 161, *High Energy Processes in Accreting Black Holes*, ed. J. Poutanen & R. Svensson, 375
- Corbel, S., Aussen, H., Broderick, J. W., et al. 2013, *MNRAS*, 431, L107
- Corbel, S., Fender, R. P., Tomsick, J. A., Tzioumis, A. K., & Tingay, S. 2004, *ApJ*, 617, 1272
- Corbel, S., Fender, R. P., Tzioumis, A. K., et al. 2000, *A&A*, 359, 251
- Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, *A&A*, 400, 1007
- Coriat, M., Corbel, S., Prat, L., et al. 2011, *MNRAS*, 414, 677
- Davis, S. W., Done, C., & Blaes, O. M. 2006, *ApJ*, 647, 525
- Dhawan, V., Mirabel, I. F., & Rodríguez, L. F. 2000, *ApJ*, 543, 373
- Diaz Trigo, M. & Boirin, L. 2012, *ArXiv e-prints*
- Diaz Trigo, M., Miller-Jones, J., Migliari, S., Parmar, A., & Boirin, L. 2011, in *The X-ray Universe 2011*, ed. J.-U. Ness & M. Ehle, 3
- Diaz Trigo, M., Sidoli, L., Boirin, L., & Parmar, A. N. 2012, *A&A*, 543, A50
- Dinger, T., Kalemci, E., Buxton, M. M., et al. 2012, *ApJ*, 753, 55
- Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, *MNRAS*, 420, 1848
- Done, C. & Diaz Trigo, M. 2010, *MNRAS*, 407, 2287
- Done, C., Gierlinski, M., & Kubota, A. 2007, *Astronomy and Astrophysics Review*, 15, 1
- Dove, J. B., Wilms, J., Maisack, M., & Begelman, M. C. 1997, *ApJ*, 487, 759
- Dunn, R. J. H., Fender, R. P., Körding, E. G., Belloni, T., & Cabanac, C. 2010, *MNRAS*, 403, 61
- Esin, A. A., McClintock, J. E., & Narayan, R. 1997, *ApJ*, 489, 865
- Fabian, A. C., Parker, M. L., Wilkins, D. R., et al. 2014, *ArXiv e-prints*
- Fender, R., Corbel, S., Tzioumis, T., et al. 1999, *ApJ*, 519, L165
- Fender, R., Wu, K., Johnston, H., et al. 2004, *Nature*, 427, 222
- Ferreira, J., Petrucci, P.-O., Henri, G., Sauge, L., & Pelletier, G. 2006, *A&A*, 447, 813
- Gallo, E., Fender, R. P., & Pooley, G. G. 2003, *MNRAS*, 344, 60
- Gierlinski, M., Zdziarski, A. A., Done, C., et al. 1997, *Monthly Notices of the Royal Astronomical Society*, 288, 958
- Joinet, A., Jourdain, E., Malzac, J., et al. 2007, *ApJ*, 657, 400
- Juett, A. M., Schulz, N. S., Chakrabarty, D., & Gorczyca, T. W. 2006, *ApJ*, 648, 1066
- Kalemci, E., Dinger, T., Tomsick, J. A., et al. 2013, *ApJ*, 779, 95
- Kong, A. K. H. 2008, *The Astronomer’s Telegram*, 1588, 1
- Kubota, A., Tanaka, Y., Makishima, K., et al. 1998, *PASJ*, 50, 667
- Laor, A. 1991, *ApJ*, 376, 90
- Luo, Y. & Fang, T. 2014, *ApJ*, 780, 170
- Malzac, J., Beloborodov, A. M., & Poutanen, J. 2001, *MNRAS*, 326, 417
- Merloni, A., Fabian, A. C., & Ross, R. R. 2000, *MNRAS*, 313, 193
- Meyer, F., Liu, B. F., & Meyer-Hofmeister, E. 2000, *A&A*, 354, L67
- Miller, J. M., Ballantyne, D. R., Fabian, A. C., & Lewin, W. H. G. 2002, *MNRAS*, 335, 865
- Miller, J. M., Homan, J., & Miniutti, G. 2006a, *ApJ*, 652, L113
- Miller, J. M., Homan, J., Steeghs, D., et al. 2006b, *ApJ*, 653, 525
- Miller, J. M., Raymond, J., Fabian, A., et al. 2006c, *Nature*, 441, 953
- Miller, J. M., Raymond, J., Fabian, A. C., et al. 2004, *ApJ*, 601, 450
- Miller, J. M., Raymond, J., Homan, J., et al. 2006d, *ApJ*, 646, 394
- Neilsen, J. & Lee, J. C. 2009, *Nature*, 458, 481
- Petrucci, P.-O., Ferreira, J., Henri, G., & Pelletier, G. 2008, *MNRAS*, 385, L88
- Plant, D. S., Fender, R. P., Ponti, G., Munoz-Darias, T., & Coriat, M. 2013, *ArXiv e-prints*
- Ponti, G., Fender, R. P., Begelman, M. C., et al. 2012, *MNRAS*, L417
- Poutanen, J., Krolik, J. H., & Ryde, F. 1997, *MNRAS*, 292, L21
- Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L., & Siemiginowska, A. 2002, *ApJ*, 571, 545
- Reis, R. C., Fabian, A. C., Ross, R. R., et al. 2008, *MNRAS*, 387, 1489
- Remillard, R. A. & McClintock, J. E. 2006, *ARA&A*, 44, 49
- Reynolds, M. T. & Miller, J. M. 2013, *ApJ*, 769, 16
- Ross, R. R. & Fabian, A. C. 2005, *MNRAS*, 358, 211
- Russell, D. M., Altamirano, D., Lewis, F., et al. 2008, *The Astronomer’s Telegram*, 1586, 1
- Rykoff, E. S., Miller, J. M., Steeghs, D., & Torres, M. A. P. 2007, *ApJ*, 666, 1129
- Salvesen, G., Miller, J. M., Reis, R. C., & Begelman, M. C. 2013, *MNRAS*
- Shimura, T. & Takahara, F. 1995, *ApJ*, 445, 780
- Sobczak, G. J., McClintock, J. E., Remillard, R. A., et al. 1999, *ApJ*, 517, L121
- Sobolewska, M. A., Papadakis, I. E., Done, C., & Malzac, J. 2011, *MNRAS*, 417, 280
- Stirling, A. M., Spencer, R. E., de la Force, C. J., et al. 2001, *Monthly Notices of the Royal Astronomical Society*, 327, 1273, (c) 2001 The Royal Astronomical Society
- Tomsick, J. A., Yamaoka, K., Corbel, S., et al. 2009, *ApJ*, 707, L87
- Wilms, J., Allen, A., & McCray, R. 2000, *ApJ*, 542, 914
- Zdziarski, A. A., Gierlinski, M., Mikoajewska, J., et al. 2004, *MNRAS*, 351, 791
- Zimmerman, E. R., Narayan, R., McClintock, J. E., & Miller, J. M. 2005, *ApJ*, 618, 832
- Zycki, P. T., Done, C., & Smith, D. A. 1998, *ApJ*, 496, L25